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DETECTION OF IONIZED GAS IN THE GLOBULAR CLUSTER 47 TUCANAE

P. C. FREIRE, M. KRAMER, AND A. G. LYNE
The University of Manchester, Jodrell Bank Observatory, Macclesfield, Cheshire, SK11 9DL, UK
F. CAMILO
Columbia Astrophysics Laboratory, Columbia University, 550 West 120th Street, New York, NY 10027
R. N. MANCHESTER
Australia Telescope National Facility, CSIRO, P.O. Box 76, Epping, NSW 1710, Australia
AND
N. D'AMICO
Osservatorio Astronomico di Bologna, via Ranzani 1, 40127 Bologna, Italy

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ABSTRACT

We report the detection of ionized intracluster gas in the globular cluster 47 Tucanae. Pulsars in this cluster with a negative period derivative, which must lie in the distant half of the cluster, have significantly higher measured integrated electron column densities than the pulsars with a positive period derivative. We derive the plasma density within the central few pc of the cluster using two different methods which yield consistent values. Our best estimate of $n_e = 0.067 \pm 0.015\,\mathrm{cm}^{-3}$ is about 100 times the free electron density of the ISM in the vicinity of 47 Tucanae, and the ionized gas is probably the dominant component of the intracluster medium.

Subject headings: globular clusters: individual (47 Tucanae) — pulsars: general

1. INTRODUCTION

Every $\sim 10^8$ yr, globular clusters pass through the plane of the Galaxy, during which any intracluster gas is expected to be stripped from the systems (Spergel 1991). However, winds from evolved stars continuously fill the cluster with gas between passages. Heretofore, numerous searches for the expected neutral and ionized material have been unsuccessful (see references in Spergel 1991; Hesser & Shawl 1977; Smith et al. 1990; Knapp et al. 1996; Penny, Evans, & Odenkirchen 1997; Hopwood et al. 1999) or inconclusive (Krockenberger & Grindlay 1995; Origlia et al. 1997b). The most convincing evidence presented so far was a $3\,\sigma$ detection of two CO lines in the direction of 47 Tucanae (henceforth 47 Tuc). These were interpreted as resulting from a bow shock formed as the cluster moves in the Galactic halo (Origlia et al. 1997a), indicating the presence of an intracluster medium. There is also an unconfirmed $3.5\,\sigma$ SCUBA detection of dust in NGC 6356 at $\lambda = 850$ nm (Hopwood et al. 1998), and a tentative detection of diffuse X-ray emission by the intracluster medium of NGC 6779 (Hopwood et al. 2000).

In this Letter we report the detection of ionized gas in 47 Tuc from new measurements of the radio dispersion of 15 of the 20 millisecond pulsars known in the cluster (Camilo et al. 2000).

2. OBSERVATIONS

Observations of 47 Tuc using the Parkes radio telescope at a frequency of 1.4 GHz have been used to measure the precise positions, periods P, and apparent rates of change of period $\dot{P}_{\rm obs}$, for 15 of its 20 known pulsars (Freire et al. 2001). We have continued timing observations of the pulsars in this cluster, and since 1999 August have used a new system providing a three-fold increase in time resolution. This consists of the central beam of the Parkes telescope multibeam receiver, as before, but uses a $2 \times 512 \times 0.5$-MHz filter bank centered on 1390 MHz, and a sampling interval of $80\,\mu$s. With these data we acquire very high quality pulse profiles, from which we obtain the precise dispersion measure for each pulsar (DM, the integrated electron column density along the line of sight from the Earth), from the relative delays in the arrival times of pulses in four contiguous 64-MHz subbands.

We do this with the TEMPO timing software[1] as follows. First we determine timing solutions for all pulsars including spin, astrometric, and binary parameters where relevant, as detailed in Freire et al. (2001), but using only data collected at 1.4 GHz (medium-resolution data during 1997 August–1999 August and high-resolution data during 1999 August–2001 February). In virtually all cases the parameters obtained are consistent at the $3\,\sigma$ level with those reported by Freire et al. (2001). We then hold the pulsar ephemerides fixed at these values, and fit for DM, using only high-resolution times-of-arrival measured in four frequency subbands. The resulting DMs are listed in Table 1, along with the $(\dot{P}/P)_{\rm obs}$, and angular offset from the center of the cluster for each pulsar, $\theta_\perp$, as determined by Freire et al. (2001).

As Figure 1 shows, all 15 pulsars are located near the center of the cluster. Having periods of a few milliseconds, they are expected to have the small positive intrinsic period derivatives $\dot{P}_{\rm int}$ which are typical of millisecond pulsars. However, the gravitational field of the cluster causes the pulsars to accelerate toward its center. The line-of-sight component a of this acceleration results in a contribution to the observed period derivative of each pulsar given by $\dot{P}/P = a/c$, where c is the speed of light. In the central regions of 47 Tuc, these values are typically greater than the $(\dot{P}/P)_{\rm int}$ for millisecond pulsars (Freire et al. 2001), so that the pulsars act as tracers of the cluster gravitational field.

[1]http://pulsar.princeton.edu/tempo

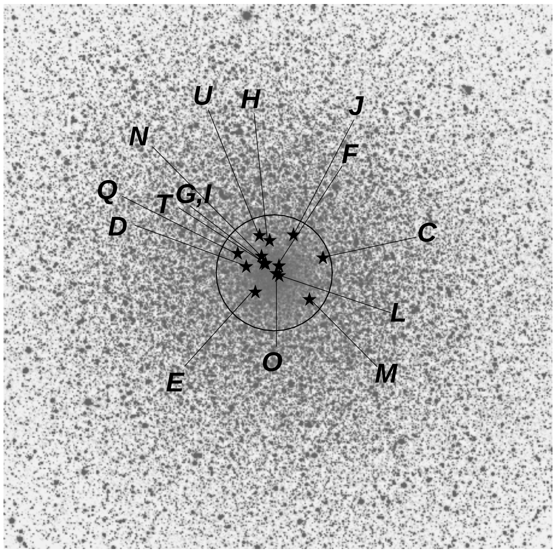

FIG. 1.— The positions of 15 millisecond pulsars in 47 Tuc superimposed on an optical image of the cluster (obtained by D. Malin, Anglo-Australian Observatory). All pulsars are located within 1.′2 (≈ 2 pc, delineated by the circle) of the center of the cluster (Freire et al. 2001). North is to the top and east is to the left.

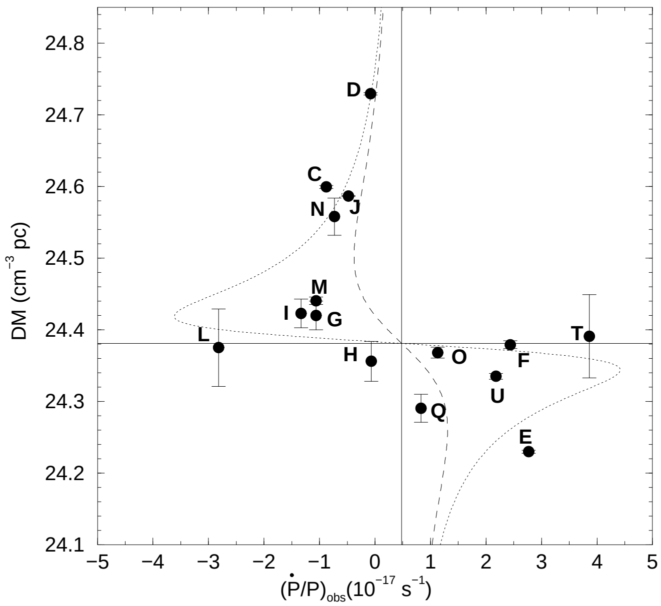

FIG. 2.— Measured DM plotted against $(\dot{P}/P)_{\rm obs}$ for 15 millisecond pulsars. Most of the pulsars with negative $(\dot{P}/P)_{\rm obs}$ have significantly higher DMs than those with positive $(\dot{P}/P)_{\rm obs}$. The curves show the expected observed variation of $(\dot{P}/P)$ with DM along lines of sight passing through the cluster core (*dotted*) and passing 2 pc from the cluster core (*dashed*). These are calculated using the cluster mass distribution described in Freire et al. (2001), assuming that all the pulsars have the same intrinsic $\langle(\dot{P}/P)_{\rm int}\rangle$, and that there is a uniform electron density of 0.067 cm^{-3} throughout the cluster. The vertical and horizontal lines represent the fitted values of $\langle(\dot{P}/P)_{\rm int}\rangle$ and DM$_{\rm c}$ as described in § 3.

Conversely, from a knowledge of the gravitational field of the globular cluster, one can use an observed period derivative to constrain the position of a pulsar in the cluster along the line of sight. In particular, pulsars located on the far side of the cluster will experience an acceleration directed towards the Earth, resulting in a negative period derivative which often exceeds the intrinsic value, leading to a negative value of $(\dot{P}/P)_{\rm obs}$. We observe this for nine of the 15 pulsars (Table 1). Figure 2 shows the measured DMs plotted against $(\dot{P}/P)_{\rm obs}$. Strikingly, most of the nine pulsars with negative $(\dot{P}/P)_{\rm obs}$, which *must* lie in the distant half of the cluster, have significantly higher DMs than those with positive $(\dot{P}/P)_{\rm obs}$, most of which are likely to reside on the near side.

We now show that this configuration is unlikely to arise by chance, by computing the chance probability of observing (as we do) the 7 pulsars with the highest DMs all having a negative $\dot{P}$ (we neglect in this calculation 47 Tuc L and T, whose DMs and uncertainties make their contribution to this argument uncertain). The number of sets of 7 pulsars among the 13 with a timing solution is $13!/(7!\times 6!) = 1716$. The number of sets of 7 pulsars among the 8 with a negative $\dot{P}$ is 8. Therefore the probability that the observed arrangement is due to chance is small, $8/1716 \approx 0.005$. It is conceivable that the observed variations in DM are simply a result of electron density variations along the different lines of sight in the interstellar medium. However this is very unlikely, because the variations in DM caused by irregularities in the Galactic electron column density are at the level $\delta{\rm DM} \sim 0.05\,{\rm cm}^{-3}$ pc over the small angle subtended by the pulsars (Nordgren, Cordes, & Terzian 1992), while the variations we observe are 10 times larger than this.

We conclude that the most likely cause of the observed DM variations is the presence of a free electron plasma within the cluster, and estimate its density in the next section.

3. PLASMA DENSITY

We derive the plasma density in the central regions of 47 Tuc using two different methods. In the first, and simpler method, the density n_e of a uniform plasma is obtained from the ratio of dispersion in measured DMs to the one-dimensional dispersion in offsets in the plane of the sky from the cluster center (Table 1):

$$n_e \simeq \frac{\sigma{\rm DM}}{\sigma(\theta_\perp D)} = \frac{0.13\pm0.04\,{\rm cm}^{-3}\,{\rm pc}}{0.75\pm0.14\,{\rm pc}} = 0.17\pm0.05\,{\rm cm}^{-3}, \quad (1)$$

where we have used $D = 5$ kpc (Reid 1998), and assume a spherically symmetric distribution of pulsars.

In the second method we calculate the positions of the pulsars along the line of sight from their period derivatives and compare these with the DMs. The measured values of $\dot{P}/P$ are biased by the intrinsic period derivative of each pulsar: with no a priori knowledge of $(\dot{P}/P)_{\rm int}$ for individual pulsars, we assume that all have the average value $\langle(\dot{P}/P)_{\rm int}\rangle$. Then, from the inferred accelerations $a/c = (\dot{P}/P)_{\rm obs} - \langle(\dot{P}/P)_{\rm int}\rangle$ and a King model for the gravitational potential of the cluster (King 1966; see Freire et al. 2001), we compute the distance R of each pulsar along the line of sight from the plane of the sky containing the center of the cluster. Here we are assuming that a King model for the potential computed with known cluster parameters, together with a relatively small contribution from $(\dot{P}/P)_{\rm int}$, provides a good description for the observed values of $\dot{P}/P$, which Freire et al. (2001) have shown to be the case. Using a uniform electron density n_e, we then calculate the incremental DM with respect to the DM to the center of the cluster, DM$_{\rm c}$, required to obtain the observed DM for each pulsar. In summary, our

model for the DMs contains the free parameters $\mathrm{DM_c}$, n_e, and $\langle(\dot{P}/P)_{\rm int}\rangle$, and is represented by

$$\mathcal{DM}_i = \mathrm{DM_c} + n_e R_i([\dot{P}/P]_{\mathrm{obs}\,i} - \langle[\dot{P}/P]_{\rm int}\rangle), \quad (2)$$

where we have noted the explicit dependence of each pulsar's line-of-sight distance R_i on the inferred acceleration. There are often two distances at which a given a/c can be obtained (see Fig. 2). We resolve this ambiguity by choosing the distance that produces a model dispersion measure $\mathcal{DM}$ closest to the observed value DM.

We determine the model parameters by minimizing

$$\mu \equiv \sum_{i=1}^{15} (\mathrm{DM}_i - \mathcal{DM}_i)^2, \quad (3)$$

and in order to obtain reliable uncertainty estimates in the derived parameters we implement this with a Monte Carlo procedure. We do so by generating 10,000 data sets where both the observed pulsar DMs and relevant cluster parameters are chosen in a random fashion consistent with their measured uncertainties (distance: 5.0 ± 0.4 kpc; Reid 1998; central stellar line-of-sight velocity dispersion: $11.6 \pm 1.4\,\mathrm{km\,s^{-1}}$; Meylan & Mayor 1986; angular core radius: $23.''1 \pm 1.''4$; Howell, Guhathakurta, & Gilliland 2000).

Minimization of μ (eq. [3]) in the Monte Carlo procedure resulted in an average and rms for the model parameters[2] of $n_e = 0.067 \pm 0.015\,\mathrm{cm^{-3}}$, $\mathrm{DM_c} = 24.381 \pm 0.009\,\mathrm{cm^{-3}\,pc}$ and $\langle(\dot{P}/P)_{\rm int}\rangle = (0.48 \pm 0.18) \times 10^{-17}\,\mathrm{s^{-1}}$. The latter corresponds to an average "characteristic age" of $\langle(P/2\dot{P})_{\rm int}\rangle = 3$ Gyr and an average magnetic field of $\approx 3 \times 10^8$ Gauss for these 15 millisecond pulsars in 47 Tuc. The line-of-sight distances R_i and uncertainties resulting from the fitting procedure are displayed in Figure 3 and listed in Table 1.

Each pulsar's $(\dot{P}/P)_{\rm int}$ is different from the average. In order to investigate the effect of this approximation in the evaluation of our model parameters we repeated the Monte Carlo procedure described above, replacing $\langle(\dot{P}/P)_{\rm int}\rangle$ with a value of $(\dot{P}/P)_{\rm int}$ for each pulsar drawn from a Gaussian distribution of characteristic ages centered on 5 Gyr with an rms of 2.5 Gyr, truncated at the low end by the limits derived by Freire et al. (2001). We repeated the procedure for a flat distribution of ages between 2 and 9 Gyr. Both distributions were chosen to be approximately representative of the distribution of characteristic ages observed for ~ 30 millisecond pulsars in the Galactic disk. The results were similar in both cases, yielding parameters smaller by about 1σ compared to the original model represented by equation (2): $n_e = 0.058^{+0.017}_{-0.012}\,\mathrm{cm^{-3}}$ and $\mathrm{DM_c} = 24.37 \pm 0.02\,\mathrm{cm^{-3}\,pc}$. Additionally, for three pulsars the inferred distances R_i or their uncertainties changed significantly, owing to the prominence of the "second solution" in $R_i(a)$ (cf. Fig. 2), and are indicated in Table 1.

Individual DMs are affected by fluctuations in the Galactic column density, as noted in § 2. There is also some uncertainty regarding the detailed form of the potential used to derive R_i from the inferred accelerations. And each pulsar's characteristic age is different from the average value determined in the model. All these factors contribute to the scatter visible in Figure 3. Nevertheless, the small scatter about the linear relation between DM and R emphasizes that the observations are consistent with two of the central assumptions made in the fit: that the cloud of ionized gas at the center of 47 Tuc is fairly homogeneous on $\sim$ pc scales, and that the King model (one simple choice amid many possible ones; see Phinney 1993) provides a consistent description for the potential of the cluster.

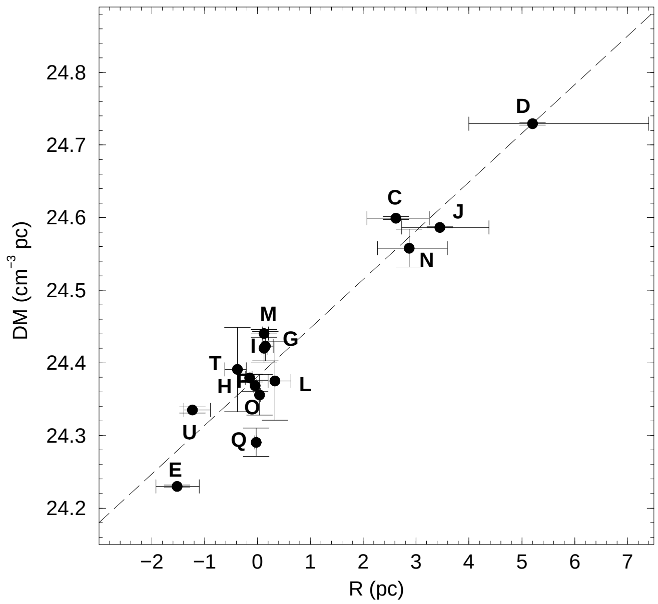

FIG. 3.— The measured DM plotted against the inferred line-of-sight distance of 15 pulsars from the plane of the sky containing the cluster center. A strong correlation is observed, for which the inferred free electron density is $0.067 \pm 0.015\,\mathrm{cm^{-3}}$.

The values of n_e derived by the methods represented by equations (1) and (2) agree at the 2σ level, although the value derived in equation (1) is nominally higher than the one derived in the Monte Carlo procedure. This is partly due to the apparently smaller effective radius of the pulsar distribution in the plane of the sky (1.9 pc; Fig. 1), than along the line of sight (3.3 pc; Fig. 3). We attribute this apparent asphericity of the pulsar distribution to small-number statistics (confirmed with a KS test), and hereafter consider the pulsars to be distributed in a sphere with effective radius the geometrical mean of the two, $r_p = 2.5$ pc. We also retain $0.067 \pm 0.015\,\mathrm{cm^{-3}}$ as the most precise estimate for n_e.

Eight pulsars with well-measured DM and $(\dot{P}/P)_{\rm obs}$ are also known in the globular cluster M15. The DM variations among these pulsars were interpreted by Anderson (1992) as arising from a gradient in the Galactic electron column density across the cluster. As an alternative interpretation, we find the data for the four millisecond pulsars ($P < 10$ ms) in M15 to be consistent with the existence of a homogeneous plasma with an electron density of about $0.2\,\mathrm{cm^{-3}}$, slightly larger than in 47 Tuc. The other pulsars in M15 have longer periods and likely have large contaminating values of $(\dot{P}/P)_{\rm int}$.

4. DISCUSSION

Using high precision pulsar timing applied to 15 pulsars observed in the globular cluster 47 Tuc, we have detected ionized intracluster gas with a density undetectable by other methods. Our measurement is consistent with previous upper limits for 47 Tuc (Hesser & Shawl 1977). The central electron

[2] In general the parameters obtained in this procedure are not Gaussian distributed. Where the difference is small we approximate to average and rms values, and otherwise present the median and one-sided "34%" error bars.

density derived, $n_e = 0.07\,\mathrm{cm^{-3}}$, compares to $\sim 0.0007\,\mathrm{cm^{-3}}$ for the ISM in the vicinity of 47 Tuc, at a z-height of 3.5 kpc, and $\sim 0.02\,\mathrm{cm^{-3}}$ in the solar neighborhood (Taylor & Cordes 1993).

With a value of $0.07\,\mathrm{cm^{-3}}$ for the mean electron density and assuming that each electron is accompanied by a single proton, we obtain a plasma mass density $\rho \sim 10^{-25}\,\mathrm{g\,cm^{-3}}$. Within the approximately spherical region of radius $r_p = 2.5$ pc occupied by the pulsars this corresponds to a total mass $\sim 0.1\,\mathrm{M_\odot}$. Recent ISO observations (Hopwood et al. 1999) put a strong upper limit of $2 \times 10^{-4}\,\mathrm{M_\odot}$ on the dust content in 47 Tuc, so that virtually any intracluster medium should be present as ionized or neutral gas. Moreover, we expect any gas present to be completely ionized: the detection of hot stars in the cluster (Paresce et al. 1991; Guhathakurta et al. 1992; O'Connell et al. 1997) indicates an intense background of UV photons, enough to ionize at least $10^{-3.5}\,\mathrm{M_\odot\,yr^{-1}}$. This is more than enough to completely ionize the $\dot{M} \sim 10^{-5}\,\mathrm{M_\odot\,yr^{-1}}$ which is lost by all the evolved stars in a typical cluster (Roberts 1986). We therefore conclude that the detected plasma represents the total intracluster medium in the inner few pc.

The inferred $\sim 0.1\,\mathrm{M_\odot}$ is much less than the $\sim 100\,\mathrm{M_\odot}$ of intracluster material expected to accumulate within r_p of the cluster core over a period of 10^7–10^8 yr (Roberts 1986). What process is then responsible for ejecting most of the gas from this region? Several different mechanisms have been proposed, most of which invoke winds such as those driven by main-sequence stars (Smith 1999), novae (Scott & Durisen 1978), M dwarfs (Coleman & Worden 1977), or pulsars. Indeed, Spergel (1991) proposed that 47 Tuc and other globular clusters should be devoid of any plasma, owing to the kinetic effects of strong winds from millisecond pulsars. Using the derived $\langle(\dot{P}/P)_{\mathrm{int}}\rangle$, the typical spin-down luminosity ($\propto \dot{P}/P^3$) of a millisecond pulsar in 47 Tuc is $\approx 10^{34}\,\mathrm{erg\,s^{-1}}$. Thus, the $\sim 10^{34}\,\mathrm{erg\,s^{-1}}$ needed to expel $10^{-5}\,\mathrm{M_\odot\,yr^{-1}}$ from the cluster's potential, which requires an escape velocity of $58\,\mathrm{km\,s^{-1}}$ (Webbink 1985), can be provided by just $\sim 0.5\%$ of the spin-down luminosity of the ~ 200 pulsars believed to exist in the cluster (Camilo et al. 2000).

If we assume that mass loss within the central few pc of the cluster is $\dot{M} \sim f \times 10^{-5}\,\mathrm{M_\odot\,yr^{-1}}$, with f of order unity (Roberts 1986), then a steady state situation implies that the plasma is being expelled from the inner $r_p = 2.5$ pc with velocity $v = \dot{M}/(4\pi r_p^2 \rho) \sim f \times 80\,\mathrm{km\,s^{-1}}$, which is comparable to the escape velocity of the cluster. Also, the existence of this plasma, together with sensitive X-ray limits on accretion luminosity from a central source, can be used to place an upper limit on the mass of a central black hole of about $100\,\mathrm{M_\odot}$ (Grindlay et al. 2001).

To conclude, we have detected the long-sought intracluster medium in a globular cluster, 47 Tucanae. It is somewhat ironic that the very objects which allow us to detect the ionized gas might also be responsible for its low concentration in the cluster.

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TABLE 1
PARAMETERS FOR 15 MILLISECOND PULSARS IN 47 TUC

Pulsar	$(\dot{P}/P)_{\rm obs}$ (10^{-17}s^{-1})	$\theta_\perp$ (arcmin)	DM (cm^{-3} pc)	R[a] (pc)
C	−0.91	1.21	24.599(2)	$+2.6 \pm 0.6$
D	−0.10	0.68	24.729(2)	$+5.2^{+2.2}_{-1.2}$
E	+2.74	0.65	24.230(2)	-1.5 ± 0.4
F	+2.42	0.19	24.379(5)	$-0.15^{+0.04}_{-0.08}$
G	−1.09	0.29	24.441(5)	$+0.12^{+0.08}_{-0.03}$
H	−0.09	0.77	24.36(3)	$+0.04 \pm 0.02$
I	−1.36	0.29	24.42(2)	$+0.15^{+0.15}_{-0.05}$
J	−0.51	1.00	24.5867(7)	$+3.4^{+0.9}_{-0.7}$
L	−2.85	0.14	24.38(5)	$+0.3^{+0.3}_{-0.1}$
M	−1.08	1.05	24.42(2)	$+0.12^{+0.06}_{-0.04}$
N	−0.76	0.49	24.56(3)	$+2.9^{+0.7}_{-0.6}$
O	+1.10	0.06	24.368(8)	-0.04 ± 0.02
Q	+0.80	0.98	24.29(2)	$-0.02^{+0.01}_{-0.03}$
T	+3.84	0.34	24.39(6)	-0.4 ± 0.2
U	+2.15	0.94	24.335(4)	$-1.2^{+0.3}_{-0.2}$

NOTE.—Uncertainties in $(\dot{P}/P)_{\rm obs}$ and $\theta_\perp$ are less than one in the least-significant digits. The values of $(\dot{P}/P)_{\rm obs}$ listed have been obtained from the actually observed values after a correction for centrifugal and Galactic acceleration (Freire et al. 2001). The uncertainties in the last quoted digits of the DMs are given in parenthesis.

[a]The line-of-sight distances from the center of cluster ($R > 0$ for the distant half) are model-dependent. We list values obtained with the model using a uniform characteristic age, represented by equation (2). For the following three pulsars, the distance or its uncertainty is different when obtained with the model where $(\dot{P}/P)_{\rm int}$ is drawn from a distribution (see § 3): $R_G = +0.2^{+2.4}_{-0.1}$, $R_M = +0.1^{+1.7}_{-0.1}$, $R_U = -0.14^{+0.05}_{-0.18}$.